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Evaluation of Prototype Secondary Hardening Steels For Armor

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Three ARL•SRG secondary hardening armor steels designed using the THERMOCALC thermomechanical database and software system were subjected to ballistic impact using U.S. .30 caliber AP M2 and U.S. .50 caliber AP M2 projectiles. Against the .30 caliber projectile, each of the three steel alloys showed ballistic tolerance comparable to AerMet® 100 Steel. Against the .50 caliber projectile, the ballistic test plates did not perform as well as AerMet 100. The results of this test series will be the basis for design and evaluation of more prototype armor steels based on secondary hardening.

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Background

During 1992 and 1993, the Steel Research Group (SRG)[1] at Northwestern University designed advanced high strength steels suitable for armor applications under contract to the Materials Directorate of the Army Research Laboratory (ARL•MD).[2] The SRG's objectives were to design precipitation hardening, prototype armor alloys and demonstrate that small additions of vanadium could be used for carbide refinement that would enhance alloy strengthening efficiency. The ARL•SRG steels were developed by computer aided design using the THERMOCALC thermomechanical database and software system.[3] Three promising compositions were prepared from ultrahigh purity iron and alloying elements. The experimental alloys, designated AX-1, AX-2, and AX-3, were characterized to determine precipitate size and distribution, hardness, fracture toughness, and heat treatment capability. The results of the investigation formed the basis for recommending heat treatment schedules for ballistic test plates.

The SRG study is related to ARL•MD's program directed at evaluating advanced steels for use in armor applications. Recently, ARL•MD presented a study on the effects of heat treatment on the ballistic properties and shear instability of AerMet 100 Steel.[4] The results of that study show that for plate thicknesses under 0.250 inch, a peak aged, mixed microstructure of M_2C and M_3C carbides performed better than the overaged microstructure consisting primarily of M_2C carbides. For thicker plate, however, the peak aged microstructure showed a tendency to fail by brittle fracture, without providing significantly improved ballistic performance.

Objective

The objective of the current tests was to evaluate the ballistic performance of material provided to ARL•MD by Northwestern University. This study gives us the opportunity to further explore the effect of microstructure on the ballistic performance of secondary hardening steels. The hardness, strength, and toughness of the ARL•SRG material is nearly equal to that of the mixed microstructure AerMet 100 Steel we studied earlier, but the microstructure of the ARL•SRG material is overaged, consisting primarily of M_2C carbides.

Material & Processing

ARL•MD received three panels of experimental steel from Northwestern University measuring approximately 25 inches long by 6 inches wide by 3/8 inch thick. The alloys were prepared for Northwestern University as 50 pound vacuum induction melted (VIM) heats.

A-1

Impurities and grain refining dispersion were controlled by means of titanium deoxidation and late rare-earth additions of lanthanum. Each melt was cast as 5 inch by 2 inch rectangular slabs, annealed at 675°C (1247 °F) for 16 hours, hot rolled at 982°C (1800°F) to 6 inch wide panels, air cooled, annealed at 677°C (1250 °F) for 16 hours, and then finish hot rolled from 982 °C (1800 °F). The chemical analysis for each heat is shown in Table 1. On delivery to ARL•MD the panels were cut to produce plates measuring approximately 12 inches by 6 inches by 3/8 inches thick.

Table 1. Desired Chemistry and Actual Chemistry

Element	Alloy AX-1		Alloy AX-2		Alloy AX-3	
(wt%)	desired	actual	desired	actual	desired	actual
C	0.27	0.21	0.27	0.30	0.27	0.30
Co	12.5	12.46	13.5	13.45	14.5	14.36
Ni	10.0	10.08	10.4	10.59	10.6	10.75
Cr	3.00	2.92	3.00	2.97	3.00	2.94
Mo	1.10	1.05	1.10	1.15	1.10	1.07
V	0.10	0.095	0.10	0.113	0.10	0.10
Ti	-	0.0142	-	0.013	-	0.01
Al	-	0.001	-	0.001	-	0.001
Mn	-	0.04	-	0.04	-	0.04
Si	-	0.02	-	-	-	0.03
Cu	-	0.01	-	0.01	-	0.01
Nb	-	0.01	-	0.01	-	0.01
Ta	-	0.01	-	0.01	-	0.01
Sn	-	0.001	-	-	-	0.001
P	-	0.001	-	-	-	0.001
S	-	0.0001	-	<0.001	-	<0.001
N	-	0.0001	-	0.0003	-	0.0003
O	-	0.0038	-	0.0028	-	0.0010

ARL•MD heat treated plates in accordance with a schedule provided by Northwestern University (see Table 2). The plates were solution treated with argon blowby in an L & L Specialty Furnace equipped with a recirculating fan. The plates were quenched in 80°F agitated oil and held for approximately five minutes. Approximately 5 to 10 seconds was required to remove the plates from the furnace and place them in the oil quench tank. After the oil quench, the plates were quenched in liquid nitrogen and held there for one hour. The time between leaving the oil quench tank and entering the liquid nitrogen quench tank was approximately 10 to 15 minutes.

The heat treatments given in Table 2 produced impressive combinations of hardness and fracture toughness. Table 3 summarizes hardness and fracture toughness for each of the three heats as reported by the SRG at Northwestern University.[2] The enhanced toughness over conventional alloy steels is in part attributable to the strain-induced transformation of metastable austenite at a crack tip.[5] This transformation toughening mechanism is controlled by the stability of the precipitated austenite formed during tempering.

Table 2. Heat Treatment Schedule

Procedure \ Material	Alloy AX-1	Alloy AX-2	Alloy AX-3
Solution Treatment	1000°C (1832°F) 1 hr, OQ	1100°C (2012°F) 1 hr, OQ	1125°C (2057°F) 1 hr, OQ
Cryogenic Treatment	-196°C (-320°F) 1 hr, AW		
Ageing Treatment(s)	482°C (900°F), 1 hr, AC & 482°C (900°F), 8hr, AC	482°C (900°F) 8 hr, AC	

OQ = Oil Quench AW = Air Warm AC = Air Cool

Table 3. Fracture Toughness and Hardness Data (from reference 2)

Property \ Material	Alloy AX-1	Alloy AX-2	Alloy AX-3
Hardness (HRC)	55.2	56.2	56.4
Fracture Toughness ($ksi\sqrt{in}$)	82.2	69.4	66.3

After heat treatment, the plates were ground to remove decarburization and scale. The final thickness for the plates from alloys AX-2 and AX-3 is 0.300 ± 0.005 inch. The two plates from alloy AX-1 differed in thickness due to grinding. Plate 1 of alloy AX-1 is 0.285 inch thick and plate 2 of alloy AX-1 is 0.218 inch thick. Twelve Rockwell C Hardness measurements were taken on the surface of each plate.

Ballistic Tests

All of the plates except plate 1 of alloy AX-1 were ballistically tested in accordance with MIL-STD-662E and Test Operation Procedure 2-2-710.[6,7] Plate 1 of alloy AX-1 was returned to Northwestern University for additional heat treatments.

Experimental Results

Table 4 shows the parameters of the ballistic tests, including the test number for each plate, the measured hardness, the projectile used, and a qualitative description of the ballistic test result. A record of partial and complete penetrations for the .30 caliber AP M2 is shown in Figure 1a; for the .50 caliber AP M2, in Figure 1b. The V_{50} velocity—the velocity at which the probability of a bullet defeating an armor plate is 50%—for each of the plates versus the 0.30 caliber AP M2 projectile is plotted in Figure 2. We have included recent data for AerMet 100 steel.[4] All of the AerMet 100 data points were obtained from plates measuring 12 inches square. As will be mentioned in the discussion, the data for AerMet 100 steel and the ARL•SRG steels may not be directly comparable. Figure 3 shows the results of AerMet 100 and the ARL•SRG steels versus the U.S. 0.50 caliber AP M2 projectile. The point shown for alloy AX-3 is not a valid V_{50} Protection Ballistic Limit (PBL), since this plate shattered after only one shot. Calculation of a valid PBL V_{50} requires a minimum of three partial penetrations and three complete penetrations within a velocity range of 125 feet per second (fps). Displayed in Figures 4 through 8 are photographs of the front and rear faces of each plate after ballistic testing.

Table 4. Ballistic Test Results

ARL•MD Test Number	Alloy	Plate Number	Measured Hardness	Projectile	Number of Shots	Result
089-94	AX-1	1	52.0 HRC	0.30 caliber AP M2	10	Plate Intact
146-93	AX-2	1	55.9 HRC	0.30 caliber AP M2	6	Plate Cracked
144-93	AX-2	2	55.6 HRC	0.50 caliber AP M2	3	Plate Cracked
147-93	AX-3	1	54.3 HRC	0.30 caliber AP M2	10	Plate Intact
145-93	AX-3	2	56.2 HRC	0.50 caliber AP M2	1	Plate Shattered

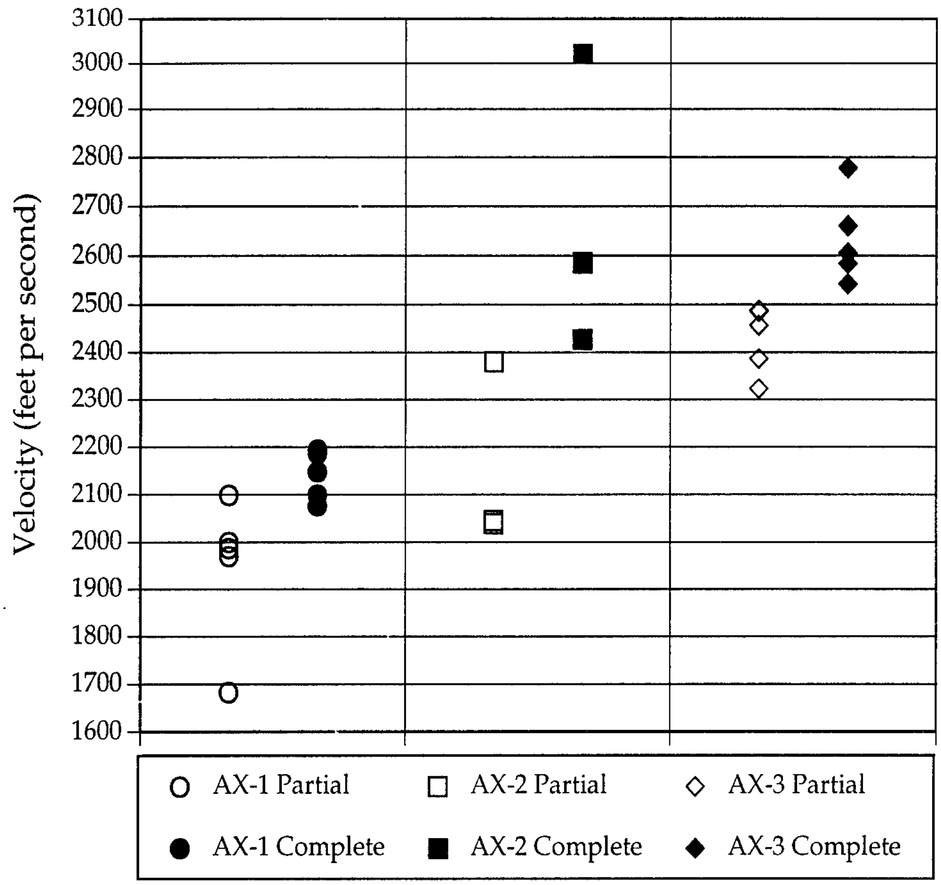


Figure 1a: Partial & Complete Penetrations for ARL•SRG Steel versus the U.S. .30 caliber AP M2 projectile

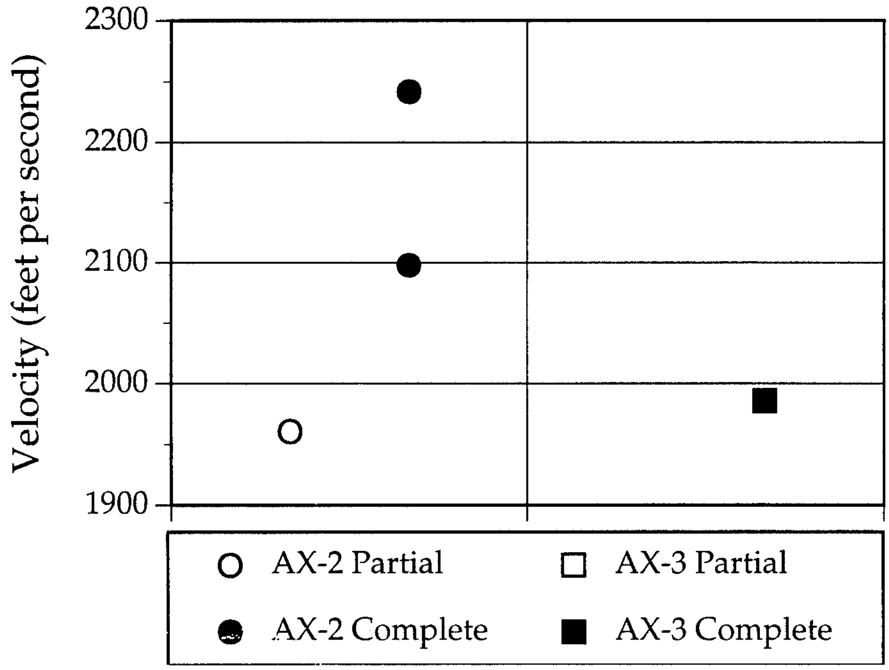


Figure 1b: Partial & Complete Penetrations for ARL•SRG Steel versus the U.S. .50 caliber AP M2 projectile

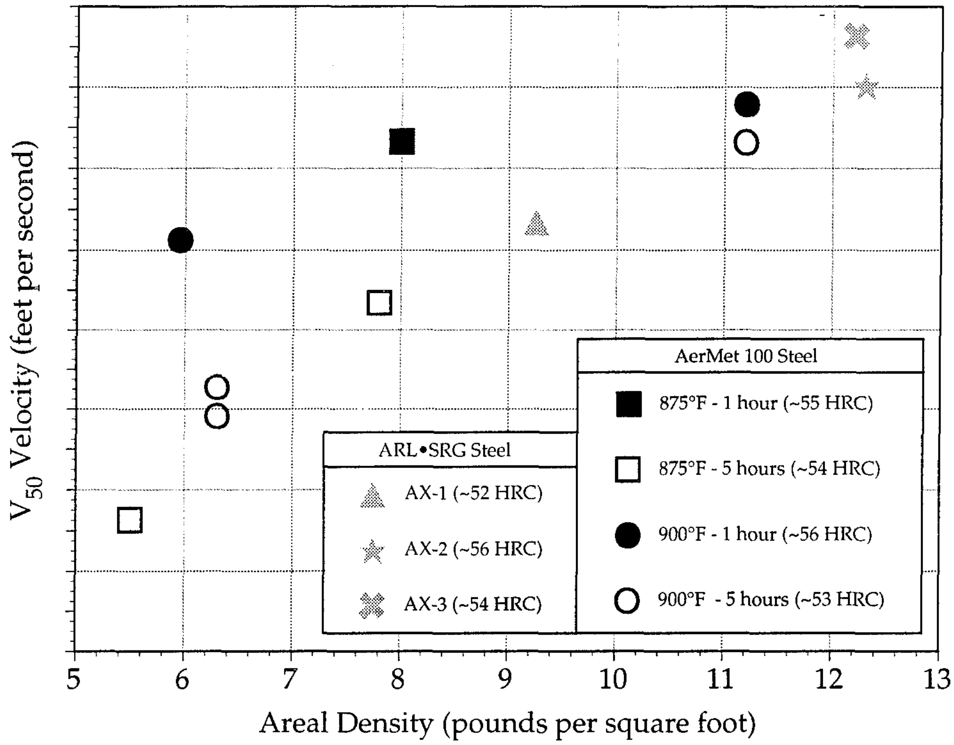


Figure 2: ARL•SRG Steel & AerMet 100 Steel versus the U.S. 0.30 caliber AP M2 projectile

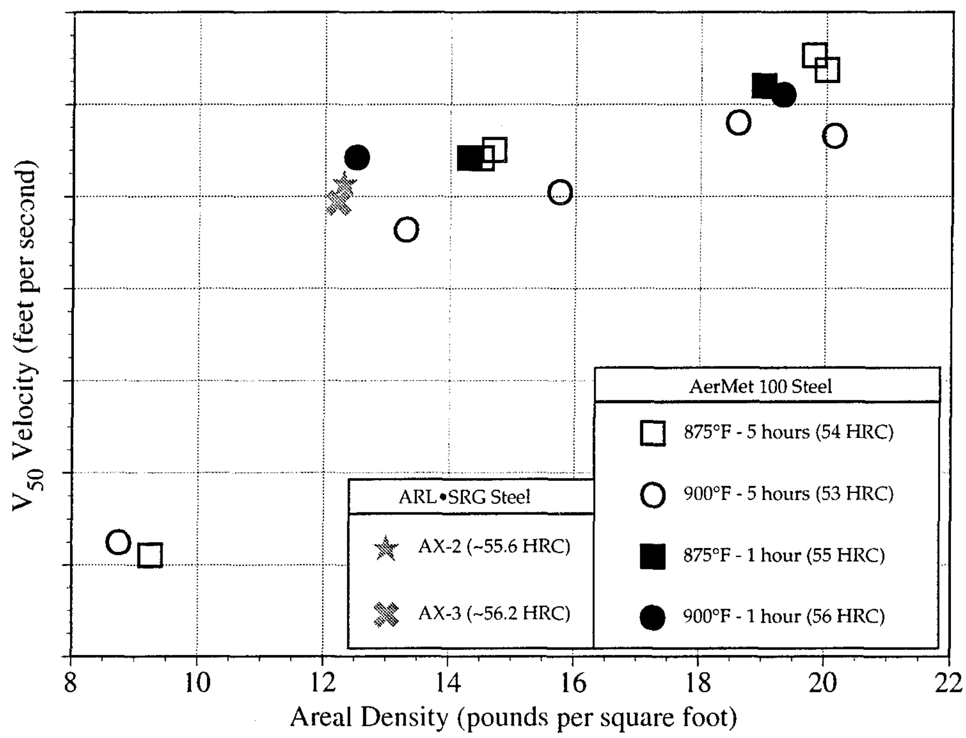


Figure 3: ARL•SRG Steel & AerMet 100 Steel versus the U.S. 0.50 caliber AP M2 projectile

Discussion

The hardness measured for alloy AX-1 is 2 - 3 points HRC lower than expected when compared to SRG data. In spite of the lower hardness, the ballistic result from .30 caliber AP M2 testing was comparable to AerMet 100 Steel in the hardness range of 52 to 56 HRC. The difference in hardness values for plates 1 and 2 of alloy AX-3 was unexpected. Both plates were solution treated and aged together, so the readings should be more consistent, as was observed for plates 1 and 2 from alloy AX-2.

The size of the plates—6 inches by 12 inches—posed some experimental difficulties on the ballistics range. The fixtures in use on the ARL•MD ballistics range are designed to accommodate plates measuring approximately 12 inches square. These plates are supported around the entire circumference by a steel frame. In the case of six inch wide plates, it was not possible to support all four sides at once using the existing fixture. We had the option of delaying testing until an appropriate fixture could be built, or proceeding with the existing fixture, modified to provide as much support as possible. We elected the latter of these two alternatives to maintain the program's schedule.

Because two of the ARL•SRG plates cracked after only a few test shots, and one failed catastrophically after a single shot, one might be tempted to conclude that toughness was insufficient. While this is a possibility, we would have expected the fourth plate to fail in a like manner if the material were the only problem. Although the fourth plate we tested (plate 1 of alloy AX-3) performed so well, and there were fixturing modifications which may have contributed to this performance, we can draw some preliminary conclusions and compare the ARL•SRG steels to AerMet 100.

Despite the low level of carbon in alloy AX-1, and the higher level of carbon in alloys AX-2 and AX-3, the performance of the ARL•SRG steels versus the U.S. 0.30 caliber AP M2 is similar to that of AerMet 100. Any excess carbon in this family of alloys can lead to reduced fracture toughness. Re-iterative design by Olson et al, suggests a carbon level of 0.25 would further improve toughness characteristics. Since the ballistic performance of alloys AX-1, AX-2, and AX-3 is nearly equal to that of AerMet 100, it is reasonable to assume that another iteration with optimized carbon content will show further improved properties.

However, it may be possible to improve fracture resistance in future ARL•SRG steels. Olson and Stephenson observed intergrannular fracture on K_{IC} specimens from the higher

carbon material (alloys AX-2 and AX-3) which were solution treated in the range of 1125 - 1150°C (2057 - 2102 °F). Microalloying with boron to enhance grain boundary cohesion may increase toughness sufficiently to reduce or eliminate fracture during ballistic impact conditions.[8]

One interesting aspect of these experimental steels is that the lower hardness material (~54 HRC) performed better than the higher hardness material (~56 HRC) during the 0.30 caliber AP M2 tests. In terms of ballistic performance, the experimental 54 HRC steel is comparable to the 55-56 HRC AerMet 100. The plate from Alloy AX-1 with a hardness of 52 HRC gave comparable performance to AerMet 100 of the same hardness.

Recommendations

1) Split and remelt a larger heat of material with optimized carbon content, half with boron and half without.

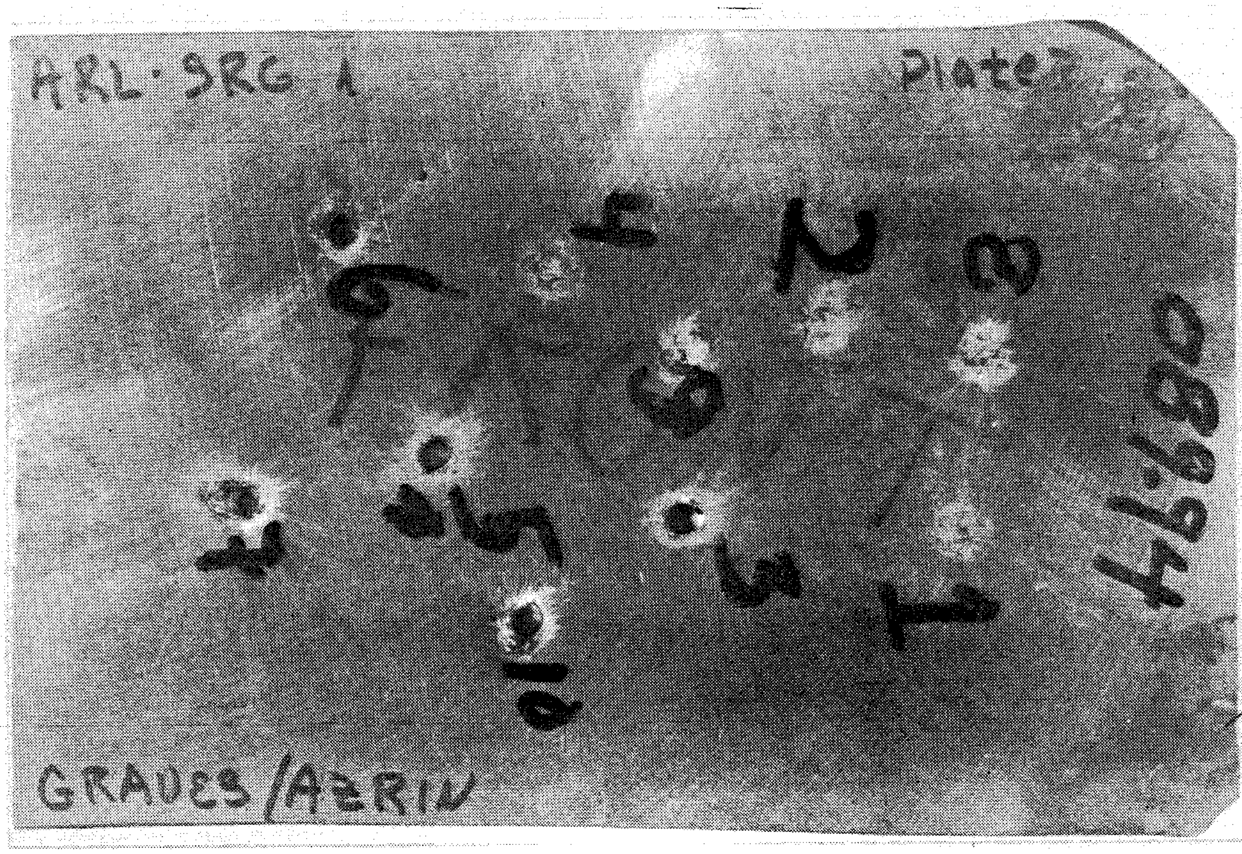
2) Roll plate material to two or three thicknesses.

3) Cut plate material to the preferred dimensions of twelve inches square for ballistic testing and evaluation.

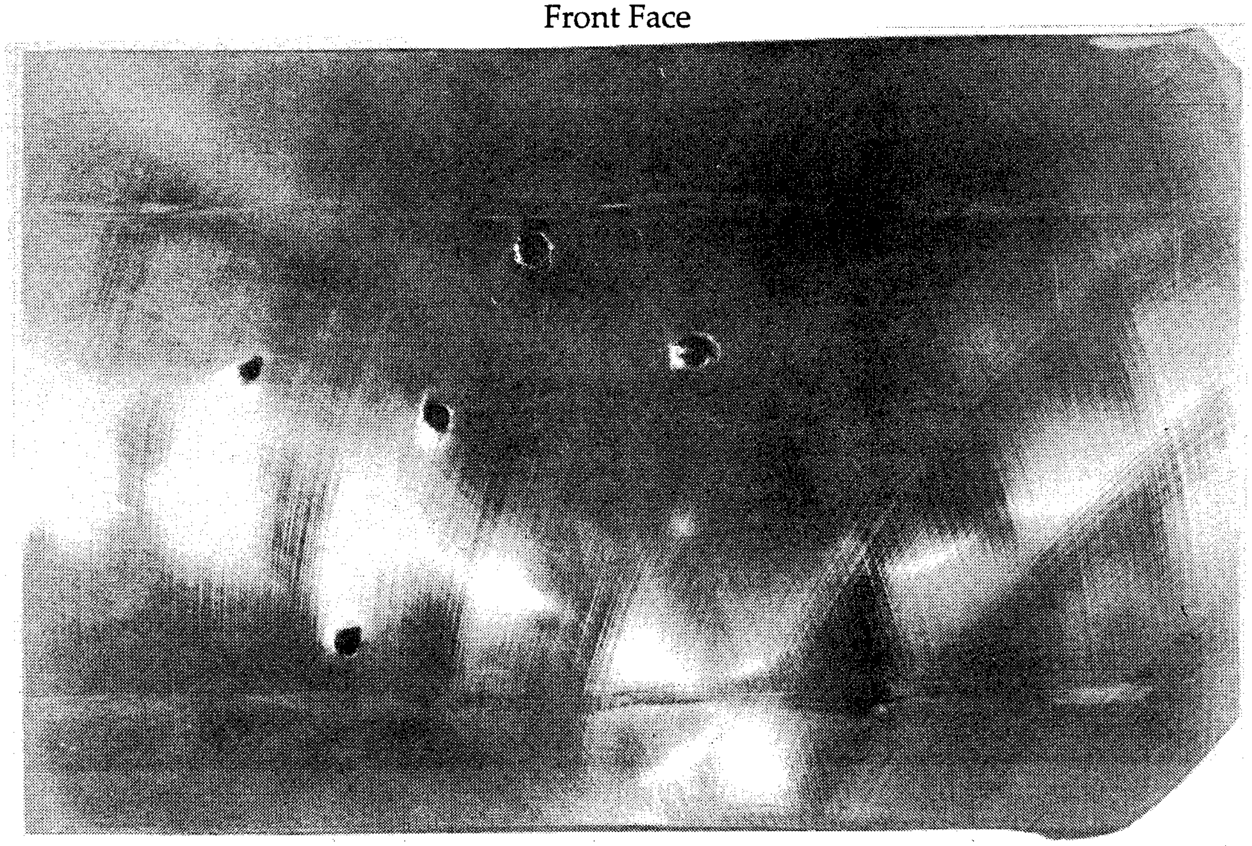
4) Determine as oil quenched and as cryogenically treated hardness after a broad range of solution treatment temperatures and use these specimens to determine prior austenite grain size as a function of solution treatment temperature.

5) Develop more detailed ageing curves for hardness as a function of tempering time at two ageing temperatures.

6) Investigate multi-step tempering treatments as a means of achieving transformation toughening.

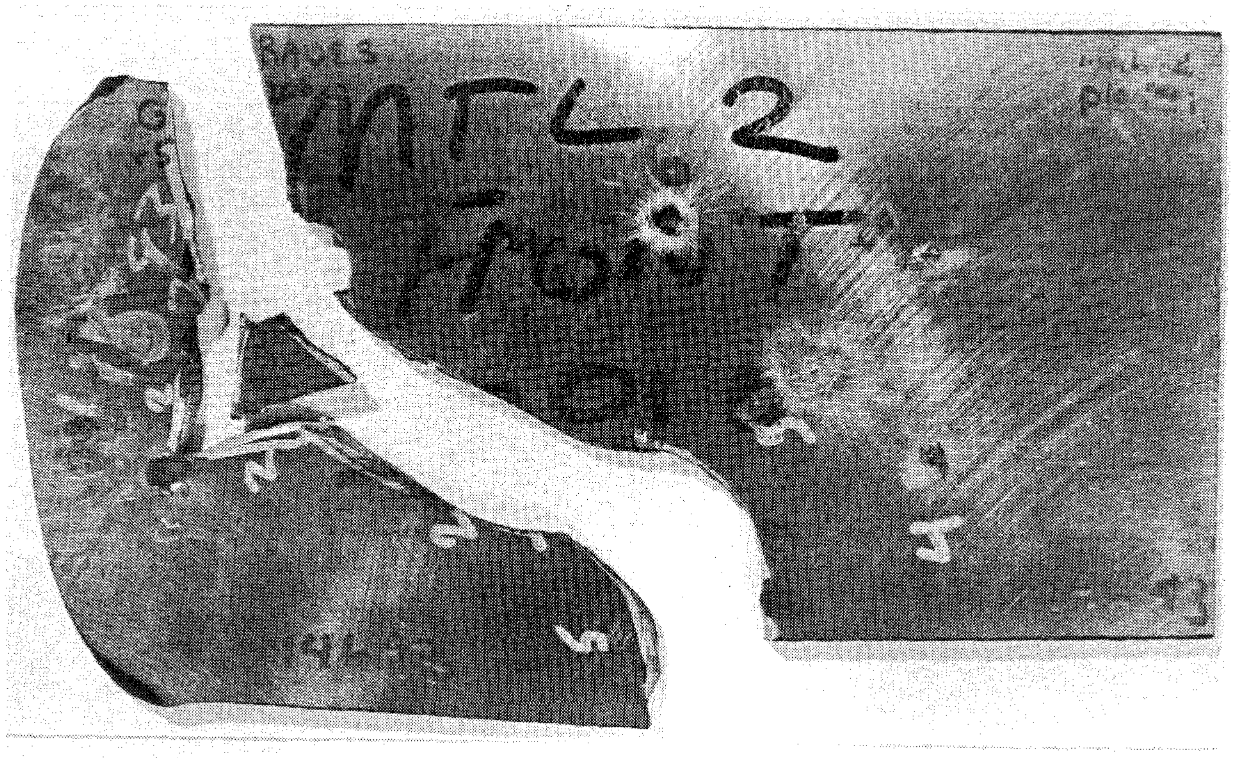


Front Face

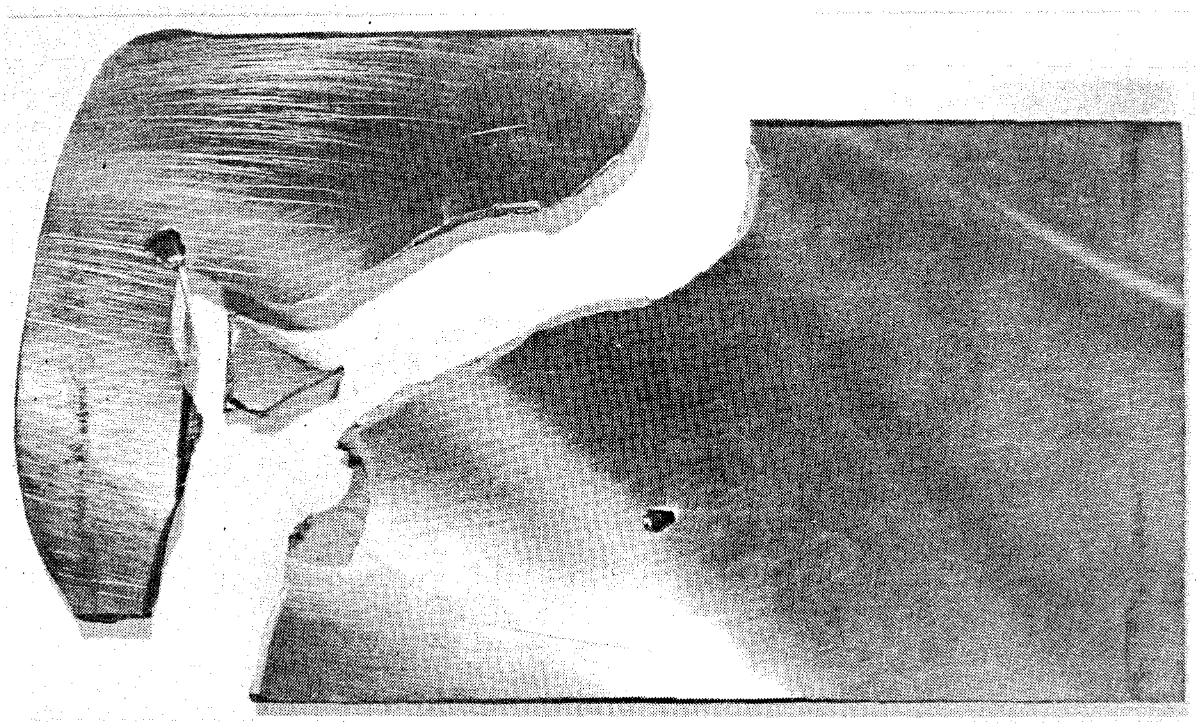


Rear Face

Figure 4. ARL•MD Test 089-94, .30 caliber AP M2 versus Plate #2, Alloy AX-1.

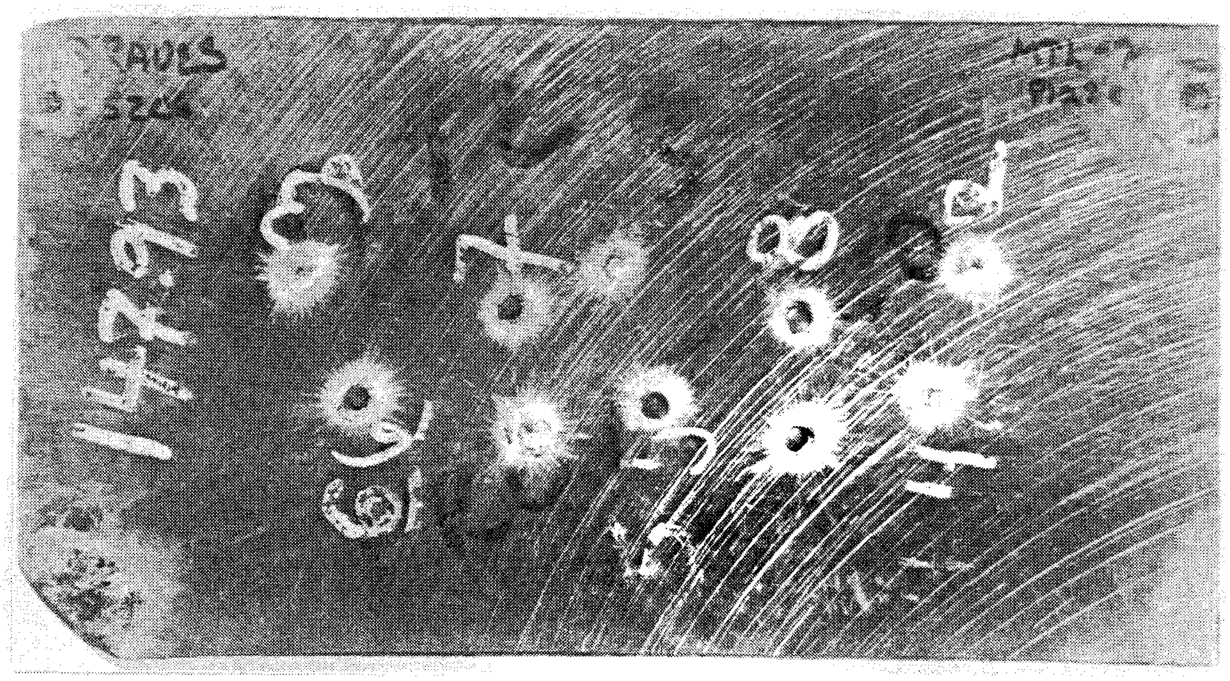


Front Face



Rear Face

Figure 5. ARL•MD Test 146-93, .30 caliber AP M2 versus Plate #1, Alloy AX-2.

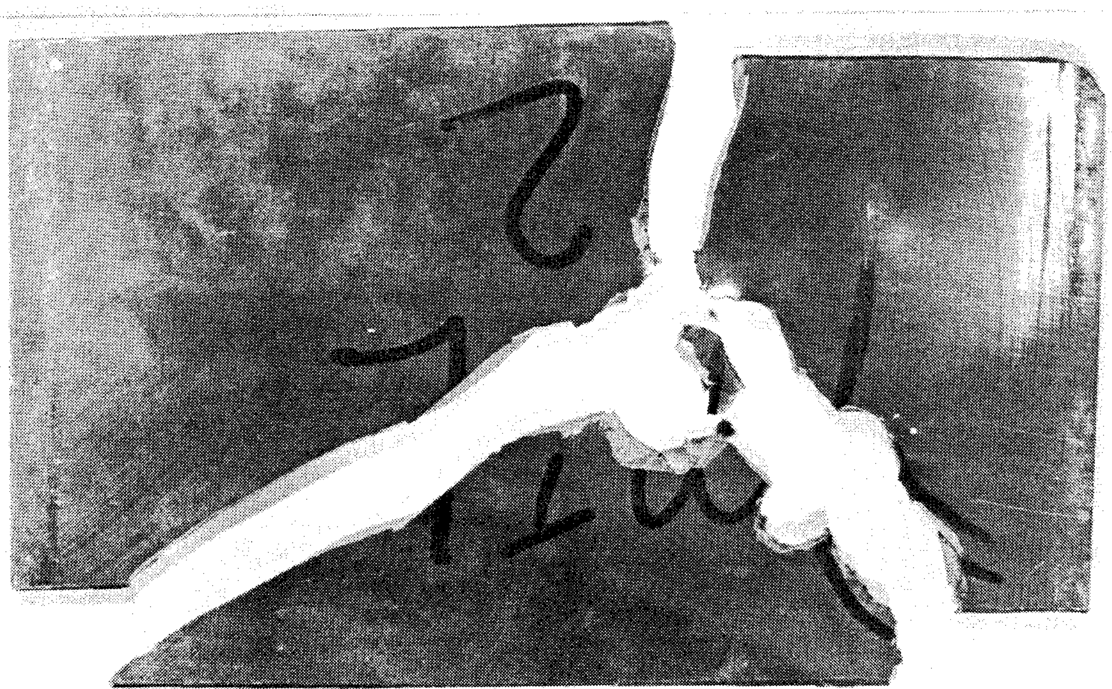


Front Face

Rear Face

Figure 6. ARL•MD Test 147-93, .30 caliber AP M2 versus Plate #2, Alloy AX-3.

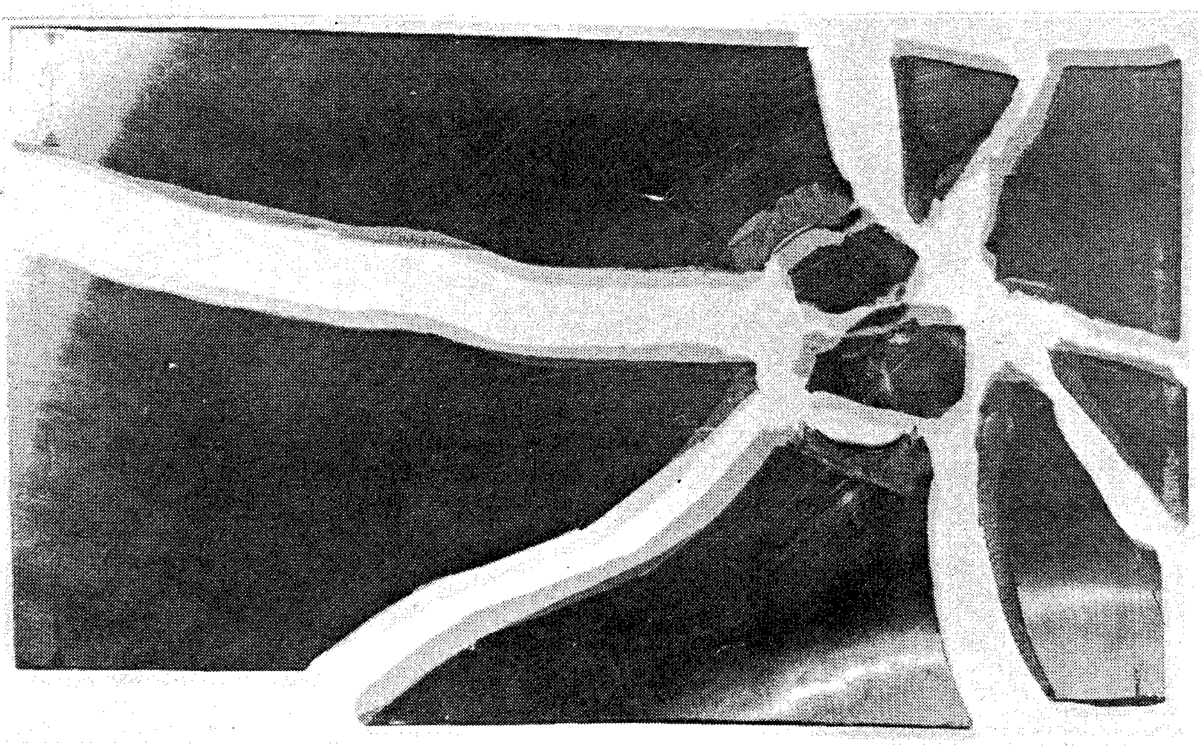
Front Face



Rear Face

Figure 7. ARL•MD Test 144-93, .50 caliber AP M2 versus Plate #2, Alloy AX-2.

Front Face



Rear Face

Figure 8. ARL•MD Test 145-93, .50 caliber AP M2 versus Plate #2, Alloy AX-3.

References

1. The SRG is an on-going multi-institutional University/Government/Industry interdisciplinary research effort originally at the Massachusetts Institute of Technology under the directorship of Dr. Gregory B. Olson. The SRG, now centered at Northwestern University, has as its research thrust the understanding of scientific principles of strength, toughness, and hydrogen embrittlement resistance to allow "first principles" design of a new generation of ultrahigh strength steels.

2. G.B. Olson and T.A. Stephenson, *Design of Advanced Steels for Armor Applications*, Final Report for U.S. Army Research Laboratory, ARL-CR-175, August 1994.

3. B. Sundman, B. Jansson, and J.O. Andersson, *Calphad*, 9, 1985, pp. 153-190.

4. J.H. Graves and J.H. Beatty, "Ballistic Performance and Adiabatic Shear Behavior of AerMet 100 Steel," in *Metallic Materials for Lightweight Applications*, Proceedings of the 40th Army Sagamore Research Conference. Editors: M.G.H. Wells, E.B. Kula, and J.H. Beatty, 1994, pp. 415-430.

5. G.N. Haidemenopoulos, G.B. Olson, and M. Cohen, "Dispersed-Phase Transformation Toughening in UHS Steels," in *Innovations in Ultrahigh-Strength Steel Technology*, Proceedings of the 34th Army Sagamore Research Conference. Editors: G.B. Olson, M. Azrin, and E.S. Wright, 1990, pp. 549-593.

6. MIL-STD-662E, V_{50} *Ballistic Test for Armor*, U.S. Army Materials Technology Laboratory, Watertown, MA, January 1987.

7. Test Operations Procedure 2-2-710, *Ballistic Tests of Armor Materials*, U.S. Army Test and Evaluation Command, Aberdeen, MD, 7 February 1984.

8. G.L. Krasko and G.B. Olson, *Solid State Communications*, V76, 1990, pp. 247-251.

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